«Investigation of Air-Sea Interaction in the Arctic on the Basis of Historical Data»

Final Technical Report

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2. Abstract

Based on both the analysis of the results of the experimental observations carried out at the Russian «North Pole - 4,5,6,28» drifting stations in 1955 - 1956 and in 1987 and on modern methods for calculating turbulent and radiation heat fluxes, the seasonal variability for parameters of air - sea ice interaction and features of heat conditions in the snow - ice cover are investigated. New results on atmospheric radiation including investigation of the role of low and upper cloudiness in formation of long-wave radiation and new parameterization of downwelling long-wave radiation are obtained. New method for estimating the characteristics of the atmospheric boundary layer together with new archive sounding data are used for estimating the characteristics of the atmospheric boundary layer in the Arctic Basin. Some new data about the temporal - spatial variability of wind drift coefficients are received.

The generalization of experience of previous experimental investigations on the drifting ice flows were used in the SHEBA planing.

Content.

Appendixes

1. Preprint of paper «Accounting for Clouds in sea ice model», submitted to Journal Atmospheric Research.

2. Preprint of paper «A Study of the Surface Heat Budget of the Arctic Ocean Based on Data from North Pole 4», submitted to Journal of Geophysical Research.

3. Historical background and introduction

Sea ice cover is a result of air-ocean interaction in the polar regions. In this connection, the successful parameterization of energy-mass exchange processes on snow or ice surfaces strongly determines the production of sea ice in prognostic and climatic numerical models. Special experiments carried out on drifting ice of the Arctic Basin during the MIZEX, AIDJEX, POLEX and LEADEX field experiments and especially during operation of 31 Russian «North Pole» drifting stations that plied the Arctic in 1937-1938, 1950-1951, then continuously during 1952-1991 provided a basis for the development of modern parameterization for this processes .

It is need to be mentioned that rarely scientists have been able to see the raw data of this experiments. Rather the information has come from the highly processed charts and tables in the Russian atlases and in comparable syntheses [Fletcher et al.,1966; Gorshkov, 1983; Treshnikov, 1985; Marshunova, 1961; Chernigovskii and Marshunova, 1965; Marshunova and Mishin, 1994].

Published analyses of data from the early «North Pole» stations [e.g., Yakovlev, 1958; Bespalov, 1959; Laikhman, 1959, Doronin, 1963, 1966; Nazintsev,1964], however, give some insights into the theory and data manipulations that went into preparing this meteorological fields. In particular, it is to note, that estimates of the turbulent heat fluxes were derived without the benefit of Monin-Obukhov similarity theory (MOST) [Monin and Obukhov, 1954], whose exposition coincided roughly with the deployment of NP-4. MOST was thus in its infancy during these early analyses. In fact, it would be 15 years before the Russian and US large scale experiments unequivocally validated the concepts of MOST and thereby confirmed the existence of the empirical similarity functions necessary for analyzing atmospheric surface layer (ASL) data in the context of the theory [Businger et al.,1971; Zilitinkevich, 1972; Haugen, 1973; Dyer, 1974; Businger, 1988; Kaimal and Wyngaard, 1990].

The upshot is that these early analyses of data from the North Pole stations were done before MOST consolidated our understanding of the atmospheric boundary layer (ABL). In particular, summary charts of turbulent surface heat fluxes over Arctic sea ice cover in some of the Russian atlases [e.g., Gorshkov, 1983] were prepared without any or only crude accounting for the effect of boundary layer stratification that MOST provides. It is well known, however, that unstable stratification enhances turbulent exchange while stable stratification suppresses it. Consequently, ignoring stratification effects belies the fundamental asymmetry of the turbulent heat fluxes in stable and unstable conditions.

The same questions arise under the calculation of radiation heat fluxes in numerical sea ice models, where together with adequate parameterization of incoming and outgoing short- and long-wave radiation, the problem of accurate description of cloudiness is very important. The atlases of Gorshkov [1983] and Prik [1965] among others give the spatial and temporal variability of several climatic variables in the Arctic basin, including charts and tables of monthly and yearly averages of total (n) and low (nl) cloudiness. This data based on generalization of information from polar land stations and Russian drifting stations through NP-7 are still the basis for describing radiative energy exchange in climatic and prognostic models of Arctic sea ice [e.g., Parkinson and Washington, 1979; Hibler, 1979; Ebert and Curry, 1993].

With the creation of a complete and corrected archive of the standard meteorological data collected on the NP stations within the framework of the Russian-American data rescue project, the opportunity for a more accurate description of cloudiness in the central Arctic and its temporal variability is now possible [NSIDC,1996].

Additional possibility to improve the existing parameterizations of energy-mass exchange processes in the system «atmospheric surface layer-snow-sea ice» and to investigate its spatial temporal variability is appeared with proceeding the data of special experiments executed on the drifting station NP-4 which had worked in the same time with drifting stations NP-5,6. The standard meteorological, aerological and actinometric observations as well as profile observations of wind velocity, air and snow (ice) cover temperatures, including melt ponds, were carried out during one year on this station. Some results of these observations were published in papers (see above) and in special data reports, but the main part of special observations remained in paper reports and never was not published.

A special experiment directed to investigation of radiation exchange between atmosphere and underlying surface was carried out during the operating period of the drifting station NP-28. Only few results of this experiment were published recently [Makshtas, Timachev, Zachek, 1995]. Additionally some information about polar cloudiness (spatial-temporal distribution of different forms) and data about

seasonal variability of parameters of atmospheric boundary layer in the central Arctic were not available up to now.

Taking in to account above mentioned, the main goals of the project were the following:

■ to develop a data base of experimental investigations at the drifting stations NP - 4, 5, 6, 28;

■ to assess the seasonal variability of the processes of energy-mass exchange between atmospheric surface layer and underlying surface and its role in setting the temperature conditions in snow and ice cover;

■ to carry out the validation of the thermodynamic sea ice model as the main part for couple model of atmosphere-sea ice-ocean circulation in the polar regions;

■ to assess the interrelation of the main meteorological parameters and energy-mass exchange characteristics in the Arctic Basin;

■ to investigate the temporal and spatial variability of the atmospheric boundary layer in the Arctic;

■ to study the role of snow cover in air-sea interaction processes.

The results of fulfillment of the project are presented in the next sections, outlined the direction of future investigations, and in two papers «Accounting for cloudiness in Sea Ice Models» (App.1) and «A Study of the Surface Heat Budget of the Arctic Ocean Based on Data from North Pole - 4» (App.2), submitted to «Journal of Atmospheric Research» and «Journal of Geophysics Research» accordingly.

4. The data set of parameters, describing air-sea interaction processes in the Arctic Basin.

During fulfillment of the project archived historical data was found and partly reconstructed. This data included meteorological, actinometric (standard and special), observations and measurements in snow and sea ice, executed on the Russian drifting stations «North Pole 4, 5, 6, 28».These data were stored in hand-written tables and only partly were processed and published. Some data, especially from the radiosoundings, needed special quality control. Also, for the original measurements of temperature profile in snow and ice as well as incoming long-wave radiation on NP-28, we had to reconstruct the calibration equations and recalculate existing data in term of physical values.

The created new data set includes the data of following observations for May 1956 - April 1957.
Drifting station «North Pole 4»:
- air temperature profile measurements at heights 5, 20, 100 , 200 cm (sometimes the humidity at the same heights) 4 times per day;
- wind velocity at heights 20 and 200 cm 4 times per day, averaged for 2-4 min;
- temperature distributions in the snow and sea ice for winter ice, 2-year ice and multiyear ice, as a rule this observations were executed once a day;
- the distribution of temperature in melt pond before, during and after freezing from surface to depth 18.5 cm, once a day from August 17, 1956 to April 4, 1957;
- standard meteorological observations for the whole period of profile measurements
(air temperature and humidity, atmospheric pressure, wind velocity and direction, total and low cloudiness amount and forms, visibility) each 3 hour;
- standard actinometric measurements (direct, diffuse, reflected and global solar radiation, long-wave radiation balance) each 6 hour, global radiation continuously (in data set represented as each hour sums);
- radiosounding observations (twice a day);
- snow depth measurements and precipitation (twice a day).
Drifting stations «North Pole 5, 6» (May 1956 - April 1957):
standard meteorological and actinometric observations every 3 hour, hourly sums of global radiation, precipitation (twice a day) and on NP-6 radiosounding observations.
Drifting station «North Pole 28» (January 1987 - December 1987):
standard meteorological and actinometric observations every 3 hour, hourly sums of global and long-wave radiation, precipitation (twice a day), radiosounding observations.
Additionally the new data set of cloudiness forms (10 species of upper, middle and low cloudiness) were created on the base of cloudiness observations, executed on drifting stations «North Pole 4, 5, 6» for period, when these three stations worked in the Arctic Basin at the same time.

5. Accounting the characteristics of energy-mass exchange between atmosphere and sea ice cover on the basis of data of special experiment on drifting station "North Pole - 4 ".

For investigations of energy-mass exchange processes between atmosphere and sea ice surface exist two approaches. First, the so-called direct method, is connected to direct measurements of vertical pulses of wind velocity and temperature. The statistical processing of measured pulses allows to receive estimations of vertical fluxes of a heat and mass without use of any additional physical assumptions and mathematical models based on these assumptions. However in the given approach large difficulties, connected as to high cost of instruments, and with complexity of operation of the equipment in field conditions, are available. Second, the so-called indirect method is based on various physical hypothesizes concerning processes of heat exchange, connecting vertical heat and mass fluxes to the characteristics of an average movement in atmosphere. The field observations of averaging characteristics of atmospheric surface layer with the purpose of reception accurate data is much easier. There are two methods of such observations: gradient and profile. With the help of gradient observations the parameters of energy-mass exchange are calculated with data about the average characteristics of atmospheric surface layer at one height and data on a surface. In this case for heat and mass fluxes account the information on temperature of surface and on parameter of dynamic roughness is necessary, that in turn represents an rather complicated problem.

Profile observations represent measurements of the average characteristics of atmospheric surface layer at several heights. There is no necessity to have the information on a condition of a surface. Moreover, on data of measurements at several heights we can calculate parameter of dynamic roughness, and in case of the assumption of equality of parameters dynamic and temperature roughness (or some another assumptions), to receive data about surface temperature . As always errors of measurements take place, the accuracy of accounts with use profile method will raise with increase of number of levels of measurements. That is, the more we shall redefine system of the mathematical equations, with the help of which distributions on height of wind velocity and air temperature are described, the estimation of heat and mass fluxes will be exacted.

The program of profile observations over the average characteristics in atmospheric surface layer was realized on drifting station " NP -4 ". In period May 1956 - March 1957 four times in days the observations over air temperature at four levels (0.2, 0.5, 1.0, and 2.0 m) and wind velocity at two levels (1.0 and 2.0 m) were executed. After data proceeding, mentioned in part 4, this data were prepared in special files for calculations of turbulent sensible heat flux and wind stress.

During the preparation of data for accounts their critical analysis for revealing casual errors formed during reading from the paper and at formation data files on diskettes was executed. At first it was the visual control with use of the software package "Lotus 123". Then analysis of extreme values was carried out with the help of Titen-Mur criterion. Revealed doubtful data were analyzed by viewing an initial material (tables of reference values) and were rejected as defective or corrected depending on the conclusion of the expert.

For calculations of turbulent heat flux (H) and wind stress (τ) the semi-empirical theory of Monin - Obukhov and the least square method were used. As well known this theory is based on a hypothesis about constancy of turbulent fluxes in the atmospheric surface layer, that enables to describe vertical structures of wind velocity and temperature with the help of so-called universal functions, taking into account effects of stratification . In a general the distribution of velocity and temperatures can be presented by the following expressions:

$$u(z_i) = \frac{u_*}{\kappa} \cdot \left[f_u(\frac{z_i}{L}) - f_u(\frac{z_{ou}}{L}) \right] ,$$

(5.1)

$$\theta(z_i) = \theta_0 + T_* \cdot \left[f_\theta(\frac{z_i}{L}) - f_\theta(\frac{z_{0T}}{L}) \right] ,$$

where κ is Karman constant (0.4); u, T are wind velocity and potential temperature at an any level z_i; u_*, T_* are the scales of velocity and temperature in surface layer; L - scale of Monin - Obukhov; f_u, and f_t are the universal functions, describing effects of stratification; z_{0u} - parameter of dynamic roughness, i.e. height, on which extrapolate under the logarithmic law wind velocity reaches the zero value; z_{0T} -

parameter of temperature roughness, i.e. height, on which extrapolate under the logarithmic law potential temperature reaches value of surface temperature To.

Entering a designations:

$$W = -\frac{u_*}{\kappa} \cdot f_u(\frac{Z_{ou}}{L}) \quad ,$$

(5.2)

$$\overline{\theta} = \theta_o - T_* \cdot f_\theta(\frac{Z_{oT}}{L}) \quad ,$$

The system of the equations (5.1) can be rewritten as:

$$u(z_i) = \frac{u_*}{\kappa} \cdot f_u(\frac{z_i}{L}) + W \quad ,$$

(5.3)

$$\theta(z_i) = T_* \cdot f_\theta(\frac{z_i}{L}) + \overline{\theta} \quad .$$

Unknown are u_*, W, T_*, θ. Formal use of a method of the least squares enables to estimate these dependent values. Thus it is necessary to determine universal functions. In algorithm were used firstly, standard assumption of equality of universal functions for wind velocity and air temperature: $f_u(z_i/L) = f_\theta(z_i/L)$. Secondly for various cases of stratification of atmospheric surface layer the following functional dependencies were accepted:

1. Stable stratification (z/L > 0):

$$f(\zeta) = \ln(\zeta) + 0.7 \cdot \zeta + 0.75 \cdot (\zeta - 14.3) \cdot \exp\{-0.35 \cdot \zeta\} + 10.7$$

2. Neutral stratification (0 ≥ z/L >(-0.07)):

$$f(\zeta) = \ln(|\zeta|) \quad f(\zeta) = \ln(|\zeta|)$$

3. Unstable stratification (z/L < -0.07)

$$f(\zeta) = 0.25 + 1.2 \cdot \zeta^{-1/3}$$

During fulfillment of work was developed and realized in form of Fortran program the numerical algorithm of the solving of system of the equations (5.3) by method of the least squares. The solution was carried out by iterations. The convergence of an iterative procedure was defined on Monin-Obukhov parameter (L). As result u_* and T_*, were calculated. After that the values of turbulent heat flux and wind stress were estimated with formulas:

$$\tau = \rho \cdot U_*^2 \quad ,$$

(5.5)

$$H = -\kappa \cdot \rho \cdot Cp \ U_* T_* ,$$

where ρ, C_p are air density and specific heat capacity.

Accounts of turbulent sensible heat flux and wind stress were carried out for each month of a researched year. Thus for each month a separate file, containing along with values of mentioned parameters the information about stratification of atmospheric surface layer, surface temperature, parameter of roughness and characteristic of conformity of restored profiles of air temperature and wind velocity to initial data was created. As examples on Fig.1, 2 the temporary variability of turbulent sensible heat flux for December and May are shown. It is necessary to pay attention to essentially large variability of H in May, a month which is transitive from winter to summer in comparison with December, typical a winter month.

In table 1 the main statistical characteristics of turbulent sensible heat flux in comparison with results of original accounts of Nazintsev (1964) are shown.

As it is possible to see from the Table 1 the calculated with described above algorithm values H not bad correspond to Nazintsev results for winter (December - February) and transition period from summer to autumn (August - October). Thus should be meant, that Nazintsev [1964] did not take into account the role of atmospheric surface layer stratification in formation of turbulent sensible heat flux.

Probably it is the reason caused the overestimation of received by him values for periods of prevailing surface cooling and connected stable stratification, suppressed turbulent exchange.

Table 1

The statistical characteristics of turbulent sensible heat flux (W/m**2) on drifting station " NP - 4 " during 1956-1957 years.

Month	Profile measurements					Nazintcev	
	Mean	msd.	Min	Max.	Mediana	Mean	
May	-3.1	17.9	-53.9	109.3	-2.6	9.4	-7.8
June	-4.5	9.0	-30.2	15.3	-3.5	3.6	4.7
July	-2.6	7.1	-38.3	10.5	-0.4	2.8	-4.7
August	1.0	3.7	-13.2	13.8	0.4	1.2	-2.6
Septembe	-1.4	5.6	-25.5	11.1	-0.1	1.9	-4.3
October	0.3	7.2	-19.0	26.8	.0	-0.9	-1.9
November	5.3	10.7	-37.9	39.0	4.8	-4.5	14.9
December	-5.9	6.6	-33.2	7.1	-4.4	-8.0	-3.6
January	-7.1	12.9	-54.0	22.8	-4.7	-10.5	-3.0
February	-3.9	8.8	-29.8	12.7	-1.2	-10.6	-7.9
Март	-0.9	16.2	-39.5	68.5	0.5	-7.3	-

The note. In the Table for a positive direction H is accepted direction from surface to atmosphere.

Much less clear is the large divergence of estimations of monthly average heat fluxes in spring-summer period. For check of Nazintsev's accounts the calculations H under the formula offered in his mentioned paper (with fixed roughness parameter and without the account of atmospheric surface layer stratification) were carried out. The results are shown in the last column. For summer the values are more close to profile estimations than published by Nazitsev.

As follows from Fig.3, constructed on initial data for May, the month when divergence between results is maximal, positive gradient of temperature (average month value of difference between temperatures measured on 200 and 20 cm) is 0.18C. One should think that it should determine negative mean value H as well as was received at accounts on our algorithm. However such conclusion is not final as the values of H are nonlinear function of a wind velocity, gradient of temperature and roughness parameter.

For investigation the influence of snow on heat balance of snow-sea ice cover the thermodynamic model, described in App.1, was used. Numerical experiments were carried out with data of drifting station «North Pole -4» for November and December 1956 for three points, characterized different thickness of snow cover (fig. 4). As boundary condition the measured sea ice temperature on depth one meter for two points on two-year ice with thickness about 2,5 m and on multiyear ice with thickness 4.35 m was used. The calculated snow surface temperatures and turbulent sensible heat fluxes are shown on fig. 5, 6. As we can see, the dependence of both parameters for thick ice on snow depth is very week..

The tables 2-4 demonstrate that practically the same results were received and for mean monthly data of all parameters of surface heat balance. It is need to note that for calculations was used quasi stationary thermodynamic model where dependence of heat conductivity on snow density was not taken into account The more extensive and accurate modeling of heat balance of .snow sea ice cover and influence of snow depth on surface heat balance were made in manuscript of paper R. E. Jordan, E. L. Andreas and A. P. Makshtas « A Study of the Surface Heat Budget of the Arctic Ocean Based on Data from North Pole 4» (App.2).

In conclusion of this part of Report we shall made the brief description of received technological production.

1. It is developed the package of the service programs realizing algorithm for calculations the characteristics of energy-mass exchange between atmosphere and sea ice surface, which allows to calculate main parameters of air-sea ice interaction with data of profile measurements.

2 The technical control of reconstructed and archived initial data, received during special heat balance experiment executed on drifting station "North Pole-4 is carried out.

3.For each month of a year and each set of measurements the values of vertical sensible turbulent heat flux and wind stress are calculated.

Table 2.

Modeled heat fluxes (W/m^2) and surface temperature (C) of multiyear ice with thickness 4.35 m.

	E_{eff}	H	LE	EH	T_0
November 1956					
mean	15.0	-7.7	2.4	8.8	-19.6
std	16.58	11.55	2.96	6.19	7.18
maximum	47.3	2.9	6.8	22.1	-3.5
min	2.5	-37.2	-3.2	-3.5	-34.6
median	4.2	-1.8	2.9	8.2	-19.0
December 1956					
mean	18.8	-10.7	1.2	8.6	-21.2
std	17.83	13.06	3.79	7.01	11.25
maximum	56.6	1.6	7.0	22.0	-3.3
min	2.8	-44.8	-13.0	-2.6	-42.6
median	4.6	-7.0	0.2	6.3	-17.9

Table 3

Modeled heat fluxes (W/m^2) and surface temperature (C) of two-year ice with initial thickness 2.35 m (point 1).

	E_{eff}	H	LE	EH	T_0
November 1956					
mean	15.2	-7.4	2.4	9.4	-19.6
std	16.33	12.08	3.17	4.25	7.27
maximum	47.3	3.2	8.8	18.6	-3.3
min	3.4	-37.2	-3.2	1.2	-34.9
median	4.4	1.8	2.8	8.8	-19.0
December 1956					
mean	18.4	-10.6	0.8	7.9	-21.4
std	17.58	13.86	3.60	4.58	11.60
maximum	56.8	2.3	7.7	16.6	-3.2
min	3.2	-44.8	-12.4	-0.1	-44.6
median	4.9	-5.8	0.0	7.3	-18.7

4. The carried out preliminary statistical analysis of received results has shown rather good conformity published data about monthly average values of vertical sensible turbulent heat flux to calculated with developed in AARI on the basis of modern parameterizations algorithm for winter conditions. In the same time a revealed significant divergence of results for spring-summer period requires strong attention during comparison of modeled and published data and additional research as from the point of view estimation of a method of account, used in Nazintsev paper as well as algorithm developed during execution of this project . We hope that it will be possible after proceeding of results, which will be received during experiment SHEBA

Table 4

Modeled heat fluxes (W/m^2) and surface temperature (C) of two-year ice with initial thickness 2.35 m (point 2).

	E_{eff}	H	LE	EH	T_0
	November 1956				
mean	14.9	-7.9	2.1	8.9	-19.6
std	16.51	11.68	3.08	6.18	7.17
maximum	46.9	2.5	6.8	21.9	-3.4
min	2.9	-38.7	-3.5	-2.2	-34.6
median	4.2	-2.0	1.8	6.5	-19.0
	December 1956				
mean	18.4	-11.2	1.2	7.6	-21.2
std	17.72	13.48	3.87	5.47	11.50
maximum	56.6	1.6	7.3	17.9	-3.3
min	2.9	-44.8	-13.0	-0.8	-43.9
median	4.4	-7.0	0.0	5.9	-17.9

6. The structure of the atmospheric boundary layer on the drifting stations «North Pole - 4, 6»

The estimation the characteristics of air-sea ice energy exchange and the height (h) of the atmospheric boundary layer (ABL) is an important problem in climate studies. In some papers [Garrat, 1993, Zilitenkevich and Chalikov A.V., 1977, Yamada, 1976] it had been developed relative simple parameterization of ABL for calculations of turbulent surface sensible (H) and latent (LE) heat fluxes and wind stress (τ) using meteorological data at the isobaric surface 850 hPa and at sea level. Danard. et. al (1983) had modified Yamada parameterization, included as internal parameter ABL height (h) and using for calculations the distributions of potential temperature (Θ), humidity (q) and wind velocity (V) in the lower layer of atmosphere from radiosoundings.

The modification of this algorithm had been worked out by Makshtas and Timachev (1994). In our method for estimations h ,H, LE and τ only synoptic information on the 850 and 700 hPa isobaric surfaces and on sea level is used. The gradients of temperature, humidity and wind velocity in the 700-850 hPa and 850 hPa -surface layers are used for reconstruction of profiles of meteorological parameters by linear interpolation. Then the Danard method is applied.

In this part we describe above mentioned methods and show some results of comparison h, estimated on the basis of standard meteorological data in atmospheric surface layer and soundings data of the drifting stations NP -4, 6 with its values calculated by Danard method and our modification together with data about characteristics of surface inversion.

The simplest method for calculations of H, LE and τ, based on the Ekman theory of ABL was developed by Zilitenkevich and Chalikov (1977). In this method the turbulent fluxes are calculated by formulas:

$$\tau = \rho \cdot V_{850}^2 c_\tau$$

$$H = -\rho \cdot C_p V_{850}(\Theta_{850} - \Theta_0) c_H$$

$$LE = -\rho L \cdot V_{850}(q_{850} - q_0) c_E \qquad (6.1),$$

where c_H, c_E, c_τ are semi-empirical functions of integral Richardson number:

$$Ri = [\frac{g}{\Theta}(\Theta_{850} - \Theta_0) + 0.61g(q_{850} - q_0)](fV_{850})^{-1}$$

and of non-dimensional external parameter $P = g/(fV_{850})$ - analogue of Rossby number, where Charnok formula for roughness parameter $z \sim U^2 /g$ is used.

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The well know semi-empirical theory of Monin - Obukhov for ABL is the background of the Yamada (1976) parameterization. The main characteristics of ABL are described in this parameterization by closed system of algebraic equations:

$$u_h = \frac{u_*}{\kappa}[\ln(\frac{h}{z_0}) - B(\mu)] \quad , \qquad v_h = -\frac{u_*}{\kappa}A(\mu)$$

$$q_0 - q_h = \frac{E}{a_v \rho \cdot \kappa \cdot u_*}[\ln(\frac{h}{z_0}) - D(\mu)]$$

$$\Theta_0 - \Theta_h = \frac{H}{a_h \rho \cdot \kappa \cdot u_* \cdot C_p}[\ln(\frac{h}{z_0}) - c(\mu)]$$

$$L = \frac{-\rho \cdot u_*^3}{\kappa\, g[\frac{H}{\overline{\Theta} \cdot C_p} + 0.61 \cdot E]} \qquad\qquad (6.2),$$

where h is the height of 850 hPa isobaric surface, u_* and L are dynamic velocity and Monin-Obukhov parameter, $A(\mu)$, $B(\mu)$, $C(\mu)$, $D(\mu)$ are empirical functions of the internal parameter $\mu = h/L$, a_v, a_h - empirical coefficients (=1.35).

In our algorithm of this parameterization the empirical functions, proposed by Yamada (1976) for $A(\mu)$, $C(\mu)$, $B(\mu)$ and by Brutsaert and Chen (1978) - for $D(\mu)$ were used. The system of the equations is solved with iteration procedure by L for z_0 =0.0015 m. The equation for module of the geostrophic wind (G) is used instead first two equations (6.2):

$$|G| = \frac{u_*}{\kappa}\left\{[\ln(\frac{h}{z_0}) - B]^2 + A^2\right\}^{1/2} \qquad\qquad (6.3)$$

In parameterization, proposed by Danard et. al (1983) the equation for height of ABL, described by Ekman scale: h = 0.3 u_*/f. is included in the system of equations (6.2, 3.3). The iteration procedure by L, and h together with radiosoundings data for each level of measurements is applied.

In our modification of Danard parameterization we use the same equations and iteration procedure but meteorological parameters for each step are calculated from its values on 700, 850 hPa isobaric surfaces and sea level by linear interpolation.

As it was mentioned we examine the possibility to calculate from meteorological data on standard isobaric surfaces the height of ABL and its connection with parameters of inversion only. For verification our results about h we use the method proposed by Mahrt (1981), who defined h as the height where a critical bulk Richardson number:

$$Ri = \frac{g}{\Theta(h)} h \frac{\Theta(h) - \Theta(0)}{|G(h)|^2}$$

exceed its critical value Ri_{cr} =0.4.

Tables 5-7 show the main statistics of ABL height for each month on drifting station NP-4 calculated by Mhart, Danard and our modification of Danard methods.

The comparison shows a best agreement between h_{Ri} and h_{mod} in month-average values. In case calculations with initial Danard method the values h are twice more. The possibility to obtain real estimations h with data only on standard isobaric surfaces allows to hope for fruitful utilization our method in climate investigations at polar regions, where sounding network is very spread.

The data about seasonal variability of inversion depth (H_t - H_b) and heights of inversion base (H_b) and top (H_t) together with corresponding temperatures T_t-T_b , T $_b$ and T_t calculated with algorithm, proposed by Serreze et. al.(1992), together with its statistics are presented in Tables 8, 9 for «North Pole 4» and in Table 10, 11 for «North Pole 6».

Table 5.

Seasonal variability of ABL height (m) on the drifting station NP-4, estimated with Danard method.

	N	mean	std	max	min	median
V	36	368	146.3	594	54	357
VI	38	434	256.3	1051	141	371
VII	41	544	243.4	1111	184	499
VIII	47	403	192.3	913	63	389
IX	38	370	179.7	822	80	348
X	39	347	211.4	739	70	343
XI	6	349	173.7	590	85	387
XII	39	385	232.7	982	76	359
I	54	424	217.9	957	76	387
II	41	346	201.8	883	40	311
III	56	415	206.5	822	55	386

Table 6.

Seasonal variability of ABL (m) height on the drifting station NP-4, estimated with modification of Danard method.

	N	mean	std	max	min	median
V	32	190	138.2	524	7	177
VI	44	297	233.1	794	7	254
VII	48	295	213.6	915	9	278
VIII	48	206	176.8	700	11	188
IX	42	230	121.8	563	38	212
X	34	182	160.7	704	13	142
XI	3	115	76.4	179	30	137
XII	32	217	168.9	681	10	137
I	32	222	154.8	541	15	179
II	26	152	169.6	562	17	72
III	21	197	213.9	635	19	86

Table 7.

Seasonal variability of ABL height (m) on the drifting station NP-4, estimated with Mhart method.

	N	mean	std	max	min	median
V	38	220	110.3	480	40	215
VI	46	313	203.1	770	70	240
VII	50	334	195.3	940	50	290
VIII	54	251	152.0	680	20	220
IX	47	229	130.5	680	50	210
X	48	194	130.6	480	10	190
XI	6	146	764.5	240	30	145
XII	46	195	134.7	520	20	165
I	59	191	140.8	570	20	150
II	48	131	110.9	570	10	110
III	56	170	86.0	340	30	150

Table 8

Repetition of inversions on drifting station NP-4

year	month	number of observations	number of inversions	number of surface inversions
1956	May	61	55	23
1956	June	60	25	4
1956	July	60	39	17
1956	August	62	49	23
1956	Septembe	60	46	31
1956	October	62	54	40
1956	November	59	52	42
1956	December	62	57	50
1957	January	62	57	52
1957	February	55	54	49
1957	March	61	61	57

Table 9.

Seasonal variability of statistical characteristics of inversions on the drifting station NP-4

	May 1956					
	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	376	-15.3	1261	-11.9	884	3.4
msd.	406.6	3.7	439.8	3.5	395.4	2.2
maximum	1600	-6.6	2100	-5.8	2100	7.8
min	0	-24.1	400	-22.2	200	0.0
median	330	-15.6	1210	-11.5	840	3.1
	June 1956					
	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	756	-9.8	1610	-7.3	853	2.4
msd	529.3	3.9	622.4	3.4	477.5	2.6
maximum	2100	-0.9	2600	-0.9	1750	7.7
min	0	-15.7	120	-13.0	120	0.0
median	760	-10.6	1770	-6.9	760	1.6
	July 1956					
	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	379	-1.7	1212	0.7	832	2.4
msd	479.1	2.0	520.3	3.0	321.2	2.0
maximum	1700	1.3	2330	5.8	1500	7.6
min	0	-6.8	420	-6.1	360	0.0
median	200	-1.2	1110	1.2	760	2.7
	August 1956					
	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	282	-2.9	1127	0.4	844	3.2
msd.	317.5	2.5	474.4	3.7	392.8	2.5
maximum	1170	0.4	2140	6.5	2140	7.9
min	0	-8.9	130	-8.9	130	0.0
median	260	-2.3	1150	1.4	800	2.7

September 1956	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	198	-11.3	1051	-7.9	853	3.3
msd.	344.4	6.2	474.9	4.7	438.6	2.7
maximum	1050	-2.1	2440	1.3	2440	13.9
min	0	-26.5	140	-19.8	140	0.0
median	0	-9.9	945	-7.6	785	2.9

October 1956	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	132	-20.8	1174	-14.3	1042	6.5
msd.	276.2	5.8	516.5	3.5	456.8	4.0
maximum	1090	-6.4	2460	-3.9	2170	16.3
min	0	-33.9	340	-20.5	260	0.2
median	0	-19.3	1085	-14.5	915	5.1

November 1956	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	57	-20.0	1100	-12.2	1043	7.8
msd.	127.7	6.9	632.9	6.0	622.0	3.4
maximum	500	-4.7	2750	-0.6	2750	16.0
min	0	-32.6	90	-23.8	90	1.1
median	0	-18.9	950	-10.0	830	8.0

December 1956	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	34	-21.2	1151	-14.1	1117	7.1
msd	107.4	8.5	642.2	5.8	622.4	4.9
maximum	630	-9.9	2830	-4.7	2830	23.0
min	0	-40.3	200	-31.6	200	0.0
median	0	-17.8	1000	-12.2	1000	5.4

January 1957	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	41	-30.3	1382	-19.4	1341	10.9
msd	152.1	9.9	758.3	8.5	753.6	6.0
maximum	940	-8.3	3430	-4.4	3430	29.2
min	0	-44.1	90	-31.5	90	0.8
median	0	-31.6	1330	-20.5	1330	11.1

February 1957	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	63	-29.5	1449	-18.6	1386	10.9
msd	256.9	9.5	666.6	6.9	683.3	4.5
maximum	1550	-6.8	2760	-4.4	2760	19.2
min	0	-43.2	200	-28.8	170	1.0
median	0	-32.2	1490	-20.5	1395	11.1

March 1957	H_b,m	T_b,C	H_t,m	T_t,C	$H_t - H_b$,m	$T_t - T_b$,C
mean	23	-29.1	1483	-18.8	1460	10.2
msd	99.8	9.8	667.6	8.4	669.8	4.3
maximum	660	-19.6	2880	-7.3	2880	21.4
min	0	-46.0	400	-36.2	400	0.0
median	0	-28.0	1410	-15.2	1380	10.1

Table 10

Repetition of inversions on drifting station NP-6

year	month	number of observations	number inversion	number surface inversions
1956	June	59	46	11
1956	July	62	43	24
1956	August	59	49	22
1956	Septembe	59	40	10
1956	October	61	51	19
1956	November	60	57	44
1956	December	62	62	40
1957	January	59	58	52
1957	February	56	56	46
1957	March	62	62	48

Table 11

Seasonal variability of statistical characteristics of inversions on the drifting station NP-6

	June 1956					
	H_b	T_b	H_t	T_t	$H_t - H_b$	$T_t - T_b$
mean	387	-5.5	1514	-1.9	1126	3.6
msd	293.9	3.8	507.8	4.7	487.2	2.7
maximum	1030	0.4	3050	9.5	2780	10.5
min	0	-14.3	520	-10.9	340	0.0
median	375	-5.5	1545	-2.2	1030	3.3
	July 1956					
	H_b	T_b	H_t	T_t	$H_t - H_b$	$T_t - T_b$
mean	236	-1.7	1390	1.3	1154	3.0
msd	411.2	2.4	601.8	4.6	488.0	3.0
maximum	1880	1.8	2810	10.8	2360	10.8
min	0	-7.0	200	-6.3	200	0.0
median	0	-1.2	1360	-0.2	1110	2.5
	August 1956					
	H_b	T_b	H_t	T_t	$H_t - H_b$	$T_t - T_b$
mean	322	-4.2	1248	-0.3	827	4.0
msd	420.2	2.8	457.0	3.5	397.3	2.8
maximum	2020	0.9	2410	6.3	1720	11.0
min	0	-11.5	470	-9.0	120	0.0
median	230	-4.1	1240	-0.4	900	3.6
	September 1956					
	H_b	T_b	H_t	T_t	$H_t - H_b$	$T_t - T_b$
mean	347	-6.7	1309	-5.0	962	1.8
msd	309.2	3.9	524.4	4.2	443.9	1.6
maximum	1160	0.1	2380	2.3	2150	5.0
min	0	-14.9	320	-11.9	170	0.0
median	290	-5.7	1315	-3.6	920	1.8

	October 1956					
	H_b	T_b	H_t	T_t	$H_t - H_b$	$T_t - T_b$
mean	345	-18.3	1348	-13.8	1003	4.5
msd	460.5	5.5	641.3	4.7	529.8	3.8
maximum	1670	-5.5	2900	-2.4	2530	17.3
min	0	-29.5	450	-22.3	130	0.0
median	200	-18.4	1180	-15.2	850	4.0

	November 1956					
	H_b	T_b	H_t	T_t	$H_t - H_b$	$T_t - T_b$
mean	155	-27.0	1434	-19.7	1278	7.3
msd	360.2	5.1	630.4	3.9	628.7	3.8
maximum	1640	-14.8	3070	-4.2	2580	14.7
min	0	-37.6	300	-26.2	300	0.0
median	0	-26.6	1420	-20.8	1230	7.4

	December 1956					
	H_b	T_b	H_t	T_t	$H_t - H_b$	$T_t - T_b$
mean	130	-27.1	1338	-18.3	1207	8.8
msd	220.9	6.8	506.6	5.4	507.4	3.9
maximum	1220	-15.8	2330	-9.4	2330	17.5
min	0	-42.5	420	-30.9	130	2.0
median	0	-24.8	1215	-17.2	1140	8.1

	January 1957					
	H_b	T_b	H_t	T_t	$H_t - H_b$	$T_t - T_b$
mean	31	-31.2	1510	-21.5	1478	9.5
msd	99.8	8.9	567.8	7.0	594.7	4.6
maximum	470	-10.6	2920	-5.1	2920	21.3
min	0	-43.7	270	-33.3	270	0.0
median	0	-31.8	1500	-22.9	1435	9.4

	February 1957					
	H_b	T_b	H_t	T_t	$H_t - H_b$	$T_t - T_b$
mean	75	-32.7	1688	-22.8	1613	9.9
msd	181.3	7.3	590.5	6.2	578.3	4.7
maximum	730	-20.3	2760	-8.4	2680	19.8
min	0	-44.7	500	-35.4	460	0.0
median	0	-32.0	1610	-22.7	1590	10.2

	March 1957					
	H_b	T_b	H_t	T_t	$H_t - H_b$	$T_t - T_b$
mean	75	-31.3	1593	-19.5	1518	11.8
msd	153.2	6.0	446.2	4.9	463.9	3.1
maximum	570	-19.2	2590	-9.4	2590	18.7
min	0	-45.4	600	-29.2	540	4.1
median	0	-29.9	1670	-18.6	1520	11.6

The comparison of seasonal variability of h in the central Arctic with seasonal variability of inversion depth and height base shows its quite different behavior during the year. From Tables 6, 7 and 9 it is possible to see that monthly averaged h_{Ri} and h_{mod} have well pronounced maximum in June (up to 330 m) and almost constant value about 160 meters in other months. In opposite inversion depth is almost constant from May to October with mean value about 850 meters and after that has a strong growth during winter to value about 1500 meters. The H_b after maximum in June gradually fall to values about 50 meters.

This peculiarities are explained by the processes of radiation cooling of low atmosphere which determines the growth the stable stratification in the ABL and suppressing of turbulent mixing to the limit determined by turbulent production due to interaction between air flow and surface. The radiation cooling also determine the continuos growth of inversion depth during winter. In opposite radiation heating of sea ice cover, including leads, maximal in June and July leads to growth of convective mixing and neutral or unstable stratification of ABL this time and to growth h and H_b.

The role of advection in formation of inversions can be demonstrated from comparison data, obtained on drifting stations NP-4 and NP-6 (tables 8-11). Especially it is evident for summer (June-July). This time NP-4 sailed near the North Pole and mean position of NP-6 was about 75-76 N, and 180 E. As a result of advection of warm air from continents and it adjustment to surface temperature (about 0 C on both stations due to melting processes) the value of $T_t - T_b$ was on NP-6 these months large than on NP-4. as well as the repeatability of surface and elevated inversions, especially in July.

Evidently that in formation of temperature regime of low atmosphere cloudiness play very important role, but it is beyond the limits of our investigation. We think that this question as well as the verification of our simple algorithm for calculations ABL height and heat fluxes with information on standard isobaric surfaces will be available after fulfillment field work under the program «SHEBA».

7. Estimation of spatial and interannual variability of the cloudiness forms on data of standard meteorological observations on drifting stations "North Pole-4,5,6".

As was shown in paper "Accounting for clouds in sea ice models" (App.1) the accurate description of cloudiness is very important for modeling of sea ice in the polar regions. In this paper the results of using different parameterizations of long wave radiation balance with account only total cloudiness in sea ice model are shown. It is evidently that total cloudiness does not give the possibility for correct estimations of influence cloudiness on short- and long-wave radiation which exceed the sea ice surface, because transparencies of low, medium and high-level clouds are quite different. Nevertheless up to now there are very few information about climatic distribution of clouds forms in polar regions.

During the work under present contract the archive of the cloudiness forms based on the data of standard meteorological observations, executed on the drifting stations "North Pole 4, 5, 6" was created. This archive includes observations over 5 groups of cloudiness for each set of meteorological observations. The representation about character of the information, contained in the archive is given by Table 12.

Table 12.

The method of description cloudiness in the archive.

Code	1 group	2 group	3 group	4 group	5 group
1	Ci	Ac	Cu	St	
2	Cc	As	Cb	Sc	Ns
3	Cs				Nbfr
4	Ci, Cc	Ac, As	Cu, Cb	St, Sc	
5	Ci, Cs				
6	Cc, Cs				Ns, Frnb
7	Ci, Cc, Cs				
8	impossible to determine due to fog, drifting snow, overlap by low cloudiness				
9	clear sky				
0	there are no clouds of any layer at presence of clouds in other layers				

The repeatability of the cloudiness forms, which means the probability of appearance of given cloudiness group in given month in cases when it is possible in principle to determine clouds from this group, was calculated for each submitted in Table 12 groups without separation into various cloudy form in limits of the group. Though this method of determination of repeatability does not allow to carry out the detailed analysis of the cloudiness forms , the reliability of received less detailed results is increased. The accounts were carried out for each month on observations fulfilled on three mentioned before drifting stations.

From all observations, executed on drifting stations NP-4,5,6 it is possible to allocate a temporary interval, when the observations were carried out on all three stations simultaneously and the position of stations was those, that its observations could characterize cloudiness in various regions of the Arctic Basin. During May - September 1956 drifting stations NP-4 and NP-5 were near the geographic North Pole. In the same time drifting station NP-6 worked in the region near the north border of the East-Siberian and Chukchi seas. The repeatability of the cloudiness forms for these months are shown in Table 13.

As it possible to see from Table 13, there are absent any systematic distinctions in repeatability of the cloudiness forms in May and June. In period from July on September it is possible to allocate certain regularity in the spatial distribution of the cloudiness forms and separate some forms with various repeatability near the North Pole and in east sector of the Arctic Basin. We can to allocate the following differences. The repeatability of cloudiness of the second group, included high-level stratified and fleece clouds, is less and in September is much less near North Pole, than in the north-east sector of the Arctic Basin. The repeatability of clouds of forth group (stratified and rainy-stratified clouds) near the North Pole in the specified months about 1.5 times more, than in the north-east sector. A little bit large repeatability of the convective forms (heap and towering clouds), making third group, is possible to allocate in the North Pole region. The last is apparently connected with advection of convective cloudiness from continent, where in summer there are the conditions for formation a similar type of cloudiness.

The influence of horizontal advection of warmer and lighter air masses from continent and their slow rise during overflow on the cold and dense arctic air explains large repeatability of high stratified cloudiness in the north-east sector of the Arctic Basin in comparison with its central part remote from land. In this region stratified clouds and undulated sheet cloudiness prevails, which, probably [Matveev, 1981], is a product of transformation frontal cloudiness system during movement of air mass above sea ice surface.

Table 13.

Repeatability of the cloudiness forms observed on the drifting stations NP-4,5,6 for period May - September 1956 (in percents).

Month	NP	1 group	2 group	3 group	4 group	5 group	coordinates
May	4	68	51	0	29	12	87.85 187.13
	5	47	39	0	43	15	86.54 78.37
	6	22	15	1	56	8	74.91 179.15
June	4	34	55	0	72	9	88.59 199.43
	5	22	33	3	61	19	86.30 64.93
	6	34	43	3	69	6	75.31 176.95
July	4	21	42	0	87	5	89.38 101.84
	5	24	38	1	79	14	84.91 68.09
	6	39	44	13	55	9	74.84 181.38
August	4	20	40	0	86	3	88.28 71.40
	5	52	38	5	68	5	84.19 76.32
	6	38	47	6	50	7	74.87 180.88
Septemb	4	26	48	0	74	2	88.21 45.91
	5	22	38	1	79	13	84.58 70.17
	6	30	70	1	57	9	75.20 176.34

Analyzing coordinates of drifting stations "North Pole-4,5,6", it is possible to note, that the observations on NP-5 in period since May 1955 to March 1956 and on NP-6 during May 1958 to March 1959 were carried out in the same region. Maximum distance between its positions in this period did not exceed 200 km. This circumstance allows to estimate interannual changes of repeatability of the various cloudiness forms during 10 months period. The distributions of clouds forms repeatability and positions of stations NP-5 and NP-6 for considered period are presented in Table 14.

Based on the data of Table 14, it is possible to make some preliminary, owing to insufficient volume of observations, conclusions about character of seasonal and interannual variability of the cloudiness forms repeatability in the central Arctic Basin. First,, the repeatability of the cloudiness forms of all groups, except group with cauliflower clouds, has significant interannual variability. The repeatability can change in some times. It is especially characteristically for stratified and rainy-stratified cloudiness (group 4 and

5). Secondly, there are the seasonal changes in the cloudiness forms repeatability. In period from November on March probability of occurrence upper cloudiness (1 group) and cloudiness of medium-level is practically the same. At that time the repeatability of stratified clouds does not exceed 30 %. In period May - October it is marked prevalence of medium-level cloudiness and stratified clouds, which probability reaches 70 %.

Table 14.

Interannual changes of clouds forms repeatability on NP-5 and NP-6 (in percents).

Month	NP	1 group	2 group	3 group	4 group	5 group	coordinates
May 1955	5	28	53	1	54	10	82.71 152.78
May 1958	6	25	5	0	59	10	81.25 147.54
July 1955	5	14	39	0	70	11	84.11 153.34
July 1958	6	28	44	0	62	8	83.45 136.12
August 1955	5	14	47	0	70	20	84.52 152.70
August 1958	6	26	48	1	51	24	84.75 124.43
Septemb.1955	5	60	70	0	69	8	84.77 145.28
Septemb.1958	6	18	31	0	57	20	85.41 113.78
October 1955	5	21	48	0	61	12	85.03 129.59
October 1958	6	24	37	0	47	2	85.31 117.00
November1955	5	19	17	0	9	5	85.70 118.73
November1958	6	19	11	0	5	0	85.95 115.57
December 1955	5	19	15	1	8	9	86.43 102.43
December 1958	6	23	32	0	17	4	86.87 96.82
January 1956	5	15	15	1	12	26	86.56 88.16
January 1959	6	32	15	0	5	4	87.12 80.61
February 1956	5	27	13	0	8	26	86.28 98.51
February 1959	6	24	11	0	22	5	86.77 61.54
March 1956	5	36	27	0	18	4	86.46 93.49
March 1959	6	42	32	0	28	3	86.40 45.57

The interannual changes of repeatability high-level and rainy-stratified are significant, while the seasonal changes are practically away. Convective cloudiness during of examined period is marked extremely seldom, repeatability in separate months do not exceed 1 %.

8. The account of cloudiness of middle and high layers at calculations of long-wave radiation.

In part 7 we showed, that any cloudiness forms have different seasonal and interannual repeatability. Ii is evident that variability of cloudiness must be reflected in empirical coefficients used in parameterizations of downwelling long-wave radiation (E_a) .In App.1 some usually used empirical parameterizations E_a with different account of total cloudiness are investigated. In this part we propose, based on paper of Girduk and Malevskii-Malevich [1981] another two empirical parameterizations E_a with account only total cloudiness and with account two characteristics of cloudiness, quantities of low and middle + high cloudiness.

Follow this paper downwelling long-wave radiation can be calculated with formula:

$$E_a = (1{,}026 T_a^2 10^{-5} - 0{,}541)(1 + k_o n_o^2),$$ (8.1),

where E_a is downwelling long-wave radiation in kW/m^2, T is air temperature in Kelvin, n_0 is amount of total cloudiness and k_0 is empirical coefficient. The first multiplier in (8.1) describes downwelling long-wave radiation at clear sky. Coefficient k_0 is determined from ratio:

$$k_o = \frac{E_{a,10} - E_{a,o}}{E_{a,o}},$$ (8.2).

where $E_{a,10}$ is long-wave radiation at overcast, which after Girduk and Malevskii-Malevich [1981] can be calculated as:

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$$E_{a,10} = 0,928 T_a^2 10^{-5} - 0,397. \tag{8.3}$$

As was shown above, the data of standard meteorological observations include data about amounts of low and middle + high cloudiness. In view of similar division E_a, as it proposes in mentioned paper, can be calculated from ratio :

$$E_a = E_{a,0}(1 + k_L n_L^2)[1 + k_{h+m}(n_o^2 - n_L^2)], \tag{8.4}$$

where n_L is amount of low cloudiness amount, k_L and k_{h+m} are coefficients for the account of influence of low and middle + high cloudiness, defined from expression, similar formula (8.2).

The long-wave radiation at total low or total middle + high cloudiness for given temperature, which values used for calculations k_L and k_{h+m} , was calculated in mentioned paper with formulas like (8.5) and (8.6) accordingly:

$$E_{a,10L} = 0,921 T_a^2 10^{-5} - 0,385. \tag{8.5}$$

$$E_{a,10h+m} = 0,964 T_a^2 10^{-5} - 0,448. \tag{8.6}$$

Using formulas (8.1-8.6) and data of standard meteorological observations, executed on drifting stations NP-4,5,6 the estimations of downwelling long-wave radiation with account of low and middle + high cloudiness (formula 8.4), and with the information only about total cloudiness (formula 8.1) were made. The calculations show that use of formula (8.1) results in overestimate E_a at presence only middle + high cloudiness 5-10 tenths up to 20% in compare with results of calculations with formula (8.4). On the other hand, in case of 8-10 tenths of low cloudiness it is observed the opposite pattern: E_a calculated with formula (8.4) on a few percents surpasses its value calculated with formula (8.1).

By the way the comparison of E_a calculated on data of timed meteorological observations and then averaged for each month and received under the same formulas, but with use of monthly average values of air temperature and cloudiness, shows that irrespective of the chosen formula for account, the monthly average values E_a, received on timed data in all months exceeds its values calculated on a monthly average meteorological data. It is necessary also to note, that in summer the distinction between values E_a, received without account and with account different kinds of cloudiness does not exceed several percents in case of use monthly average data.

As check of the used empirical formulas the comparison of results received under formulas (8.1) - (8.6) with data of direct measurements of downwelling long-wave radiation, carried out on the drifting station "North Pole-28" in March - October 1988 was made. For this purpose special data sets was created: for the clear sky (cloudiness amount 0/0 or 1/0) - 167 observations; for total low cloudiness (10/10) - 578 observations; for total middle and high cloudiness (cloudiness amount 10/0) - 104 observations. For these data sets which include also data about air temperature and downwelling long-wave radiation with the least square method the new formulas for account E_a were obtained:

for clear sky:

$$E_{a,0} = 0,614 \cdot T_a^2 \cdot 10^{-5} - 0,227 \tag{8.7}$$

for total middle and high cloudiness:

$$E_{a,10}^{h+m} = 0,845 \cdot T_a^2 \cdot 10^{-5} - 0,337 \tag{8.8}$$

for total low cloudiness:

$$E_{a,10}^L = 0,891 \cdot T_a^2 \cdot 10^{-5} - 0,364 \tag{8.9}$$

Use in calculations under the formulas (8.1) and (8.4) expressions (8.7) -(8.9) instead of (8.3), (8.5), (8.6) for the whole specified period has allowed to receive values of downwelling long-wave radiation with average absolute errors 15 W/m^2 for the formula (8.1) and 13 W/m^2 for formula (8.4). Originally, with formulas, proposed by Girduk and Malevskii-Malevich [1981] the error exceeded 29 W/m^2.

The calculations E_a were also carried out with formulas, where influence of cloudiness was parameterazed with linear function on cloudiness amount:

$$E_a = E_{a,0}(1 + k_o \cdot n_o) \tag{8.10}$$

$$E_a = E_{a,0}[1 + k_L \cdot n_L + k_{h+m} \cdot (n_o - n_L)] \tag{8.11}$$

Also the seasonal dependence of coefficients in formulas for clear sky, total low and total middle + high was investigated. For this purpose all data of E_a obtained on NP-28 with infra-red radiometer were divided in two data sets, containing data of observations executed during June - September and

observations, executed in transitive seasons: March - May and October. After the least square method was used to obtain formulas, similar (8.7) - (8.9), but for different seasons:

for summer (June - September):

$$E_{a,0} = 0{,}762 \cdot T_a^2 \cdot 10^{-5} - 0{,}314 \qquad\qquad (8.12),$$

$$E_{a,10}^{h+m} = 0{,}853 \cdot T_a^2 \cdot 10^{-5} - 0{,}334 \qquad\qquad (8.13),$$

$$E_{a,10}^L = 0{,}784 \cdot T_a^2 \cdot 10^{-5} - 0{,}290 \qquad\qquad (8.14),$$

for transitive seasons (March-May, October):

$$E_{a,0} = 0{,}805 \cdot T_a^2 \cdot 10^{-5} - 0{,}041 \qquad\qquad (8.15),$$

$$E_{a,10}^{h+m} = 0{,}855 \cdot T_a^2 \cdot 10^{-5} - 0{,}341 \qquad\qquad (8.16),$$

$$E_{a,10}^L = 0{,}757 \cdot T_a^2 \cdot 10^{-5} - 0{,}284 \qquad\qquad (8.17).$$

The comparison between calculated and measured values of downwelling long-wave radiation showed, that the average absolute errors for formula (8.10) are 13 W/m^2 and 15 W/m^2 for summer and transitive seasons accordingly. For formula (8.11), taking into account cloudiness of different layers these errors are 11 W/m^2 and 14 W/m^2.

Based on results discussed above we can make the following conclusions.

1. The new formulas for calculating downwelling long-wave atmospheric radiation for clear sky and overcast, using as the initial information only air temperature together with formulas taking into account cloudiness of different layers are received. In contrast to usually used empirical formulas for E_a with constant coefficient k, in our formulas k is a function of air temperature. It is, our opinion, give possibility more accurate to account the influence of thermal state of cloudy atmosphere on downwelling long-wave radiation.

2. The formulas for calculation E_a using quadratic and linear dependence on a cloudiness amount, give almost the same results, i.e. the average absolute error actually coincides. In the same time the account of different cloudiness allows to reduce mean errors on 2 W/m^2.

3. The adjustment of empirical formulas, created by Girduk and Malevskii-Malevich [1981] to data of instrumental measurements E_a , executed on drifting station NP-28 allowed to improve coefficients in formulas for clear sky and overcast, that has resulted in reduction in two times of the average absolute error at calculation of downwelling long-wave radiation.

9. Characteristics of ice drift patterns on data of observations on drifting stations "North Pole-3,4,5,6".

The characteristics of ice drift are one of major at development prognostic and climatic models of circulation waters and ice in Arctic Basin. One of possible ways to account these characteristics on the basis of empirical data is a physical-statistical method, developed in AARI [Gudcovich,1965,1985]. This method is allows to estimate wind coefficients and components of surface currents on data of drifting station position and measured surface wind velocity.

For calculation of the specified parameters for regions where drifting stations "North Pole 3,4,5,6" worked (Fig.7) the preparation of initial data was preliminary carried out. For this purpose on each pair of consecutive coordinates of station drift velocities for periods between astronomical observations were calculated. From data of standard meteorological observations the mean wind velocity components were calculated and averaged for the same period. Thus concurrent rows containing data on components of a wind and drift velocities for identical periods were received. During analysis the received rows were divided into necessary intervals depending on a type of researched drift variability (monthly, seasonal and etc.).

The further data processing was based on the following reasons about connection of vectors of a wind and drift velocities. Let V, C, W and U are the vectors of wind, constant current, wind and total drift velocities, β - direction of a wind velocity, α - angle between wind drift and wind velocities.
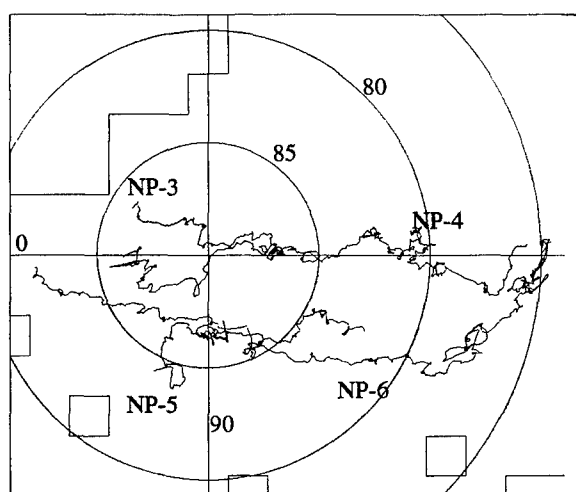
Thus U = W + C.

Fig 7. Drift of the «North Pole» stations.

We propose, that the wind drift velocity is proportional to a wind velocity:

W = kV   (9.1),

where k is wind coefficient.

The formulas for drift velocity components can be presented as:

$U_x = W \sin(\alpha + \beta) + C_x$ $U_y = W \cos(\alpha + \beta) + C_y$.   (9.2).

For wind velocity components we have:

$V_x = V \sin\beta.$, $V_y = V \cos\beta$ and $tg\beta = V_x / V_y$ (9.3).

By substituting the formula (9.1) in the equations (9.2) and expressing with the formulas (9.3)   V and β through V_x, V_y and α we receive:

$U_x = V_x k \cos a + V_y k \sin a + C_x$ $U_y = V_y k \cos a - V_x k \sin a + C_y$ (9.4).

With a rather large numbers of meanings U_x, U_y and appropriate V_x and V_y, we can write two systems of the conditional equations :

$U_{xi} = a1 V_{xi} + b1 V_{yi} + c1$ $U_{yi} = a2 V_{yi} - b2 V_{xi} + c2$ (9.5).

Solving each of equations (9.5) with method of the least squares , we receive the appropriate regression equations . From comparison (9.4) and (9.5) it follows:

$a = k \cos\alpha$, $b = k \sin\alpha$, $c1 = C_x.$, $c2 = C_y$ and $\alpha = arctg (b/a)$, $k = (a^2 + b^2)^{0.5}$.

The results of accounts for each of the drifting stations are shown in Table 15. The table contains the results of accounts on the equations (9.5) for each row of observation. In it coefficients a, b and c for each of the equations (9.5) are included together with coefficient of linear multiple correlation R, which shows what part of dispersion of drift velocity components is caused by changes of wind velocity in previous days. The value of multiple correlation coefficient shows, as far as exact would be the forecasts carried out with the help of the regression equations . The coefficient σ_Δ/σ_W, showing what part of the dispersion of deviation of calculated component of drift velocity from observed is relatively to dispersion of the observed component during temporal period under study, is shown in the last column of the Table 15. Besides in the next part of the Table 15 the wind factors k_x, k_y, k and angles of a deviation of wind drift velocity from wind velocity (α) together with calculated direction of constant current (α_c) and its module (|C|) are shown. As it is visible from the table the connection of ice drift and wind has appeared rather close.

For revealing the seasonal variability of relation between wind and drift velocities the files for each month of a year , including the information of all drifting stations under consideration were made. The results of accounts are presented in Table 16 and on Fig.8. It is visible, that in summer the angle between vectors of drift and wind is increased from 27 up to 42 degree. Taking into account smaller thickness of ice in summer, and consequently smaller Coriolis force (at the same drift velocity), it would be possible to expect and smaller angle of the deviation. Probable reason of increase of the deviation angle in summer consists in reduction of water stress on the bottom border of an ice cover owing to smaller hydrodynamic roughness of the bottom surface of young ice and also increase of stability owing to freshening ocean upper

layer . The magnitude of wind factor K has an expressed minimum in winter period, caused by increase of sea ice compactness due to freezing of leads and increase of strength of sea ice.

<div align="right">Table 15</div>

The main characteristics of the drift in the central Arctic on data of drifting stations.

NP-3 (Number of observations   261)

i	a	b	c	(σ_Δ/σ_w)	R
1	0.013	0.009	0.012	0.83	0.95
2	0.014	0.008	0.003	0.71	0.97

K_x	K_y	K	α	α_c	C(m/s)
0.015	0.017	0.016	32	75	0.012

NP-4 (Number of observations   856)

i	a	b	c	(σ_Δ/σ_w)	R
1	0.012	0.007	0.000	0.67	0.97
2	0.014	0.008	0.011	0.78	0.94

K_x	K_y	K	α	α_c	C(m/s)
0.014	0.016	0.015	30	0	0.011

NP-5/1 (Number of observations   27)

i	a	b	c	(σ_Δ/σ_w)	R
1	0.016	0.007	0.005	0.33	0.99
2	0.012	0.007	0.012	0.47	0.99

K_x	K_y	K	α	α_c	C(m/s)
0.017	0.014	0.016	27	22	0.013

NP-5/2 (Number of observations   342)

i	a	b	c	(σ_Δ/σ_w)	R
1	0.014	0.010	-0.019	0.50	0.98
2	0.012	0.008	-0.001	0.88	0.92

K_x	K_y	K	α	α_c	C(m/s)
0.017	0.014	0.016	34	-92	0.019

NP-6 (Number of observations   936)

i	a	b	c	(σ_Δ/σ_w)	R
1	0.012	0.006	-0.011	0.60	0.98
2	0.012	0.009	0.000	0.55	0.98

K_x	K_y	K	α	α_c	C(m/s)
0.014	0.015	0.014	33	-89	0.011

It is evidently, that the results discussed above, based on historical data , have some uncertainty connected with inaccuracy of astronomical observations and different time intervals between its executions, connected with weather conditions. But now when GPS devices allows to determine positions with high accuracy the physical-statistical method, described in this part can serve at least as a tool for estimation of surface currents and validation of dynamic-thermodynamic models of sea ice
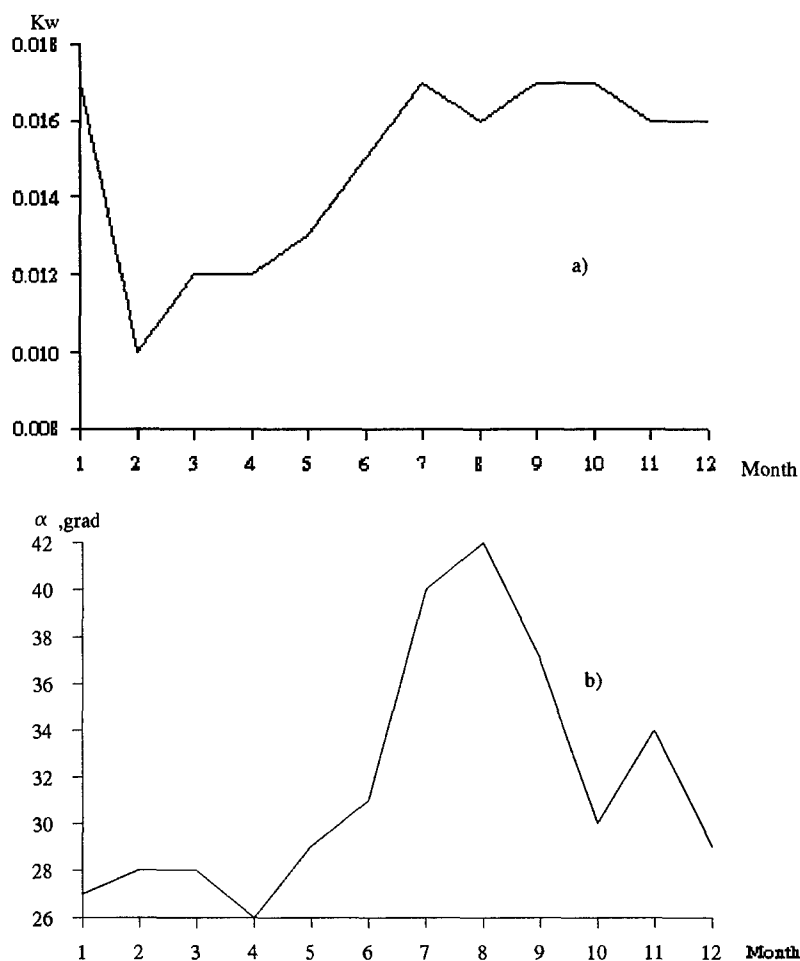
Fig 8. Seasonal variability of the connections of the ice drift and wind
a) seasonal variability of k_w
b) seasonal variability of the angle between wind and drift vectors

Table 16.

Seasonal variability of the main parameters of the drift in the central Arctic

Month	K_x	K_y	K	α	α_c	C, m/s	Nobs
January	0.016	0.018	0.017	27	140	0.004	213
February	0.012	0.008	0.010	28	-101	0.007	188
March	0.011	0.012	0.012	28	-65	0.012	213
April	0.011	0.012	0.012	26	-114	0.004	206
May	0.012	0.013	0.013	29	-67	0.013	253
June	0.014	0.016	0.015	31	-47	0.012	222
July	0.017	0.018	0.017	40	-25	0.012	213
August	0.015	0.018	0.016	42	-43	0.015	187
September	0.017	0.017	0.017	37	-39	0.014	151
October	0.015	0.019	0.017	30	-60	0.006	153
November	0.017	0.016	0.016	34	-18	0.007	207
December	0.016	0.016	0.016	29	-8	0.001	216

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Conclusion.

During the fulfillment of the project the new data set of parameters, describing air-sea interaction processes in the Arctic Basin was created. Almost all data about atmosphere and sea ice obtained during first complex experiment, executed on the drifting ice 45 years ago were reconstructed, collected and now available for scientists.

Some new results about the characteristics of energy-mass exchange between atmosphere and sea ice cover and structure of the atmospheric boundary layer were received with modern algorithms partly developed during work under this project. These data served as a base for development and validation of , our opinion, the most complete thermodynamic model of spatially homogeneous sea ice cover (App.2).

The new results were obtained about seasonal and spatial variability of characteristics of inversions and atmospheric boundary layer in the central Arctic Basin and its periphery due to simultaneous observations during ten months of drifting stations «North Pole 4» and «North Pole 6».

The analysis of spatial and interannual variability of the cloudiness forms, executed on data of meteorological observations on drifting stations "North Pole-4,5,6", showed that the repeatability of the cloudiness forms of all groups, except cauliflower clouds, has significant interannual variability. Also was revealed the seasonal changes in the cloudiness forms repeatability.

Using the comprehensive archive of cloudiness for drifting stations «North Pole 4, 5, 6, 28», data of direct measurements of downwelling long-wave radiation, executed on NP 28 and original algorithm never used for estimations of incoming infrared radiation in polar regions, the new parameterizations for account this parameters of surface heat balance were developed. The main difference of this parameterization from another is the direct dependence of coefficient, considering the influence of cloudiness on IR-radiation, on thermal conditions in cloudy atmosphere.

The algorithm, developed in AARI, together with created data set allowed to investigate characteristics of ice drift patterns in the central Arctic Basin and revealed its seasonal variability.

In whole during the work under the project we tried to investigate on the base of historical data the most important air-sea ice interaction processes in the polar regions and outline the direction of future investigations with data of the complete modern experiment SHEBA executes on the Arctic drifting ice now.

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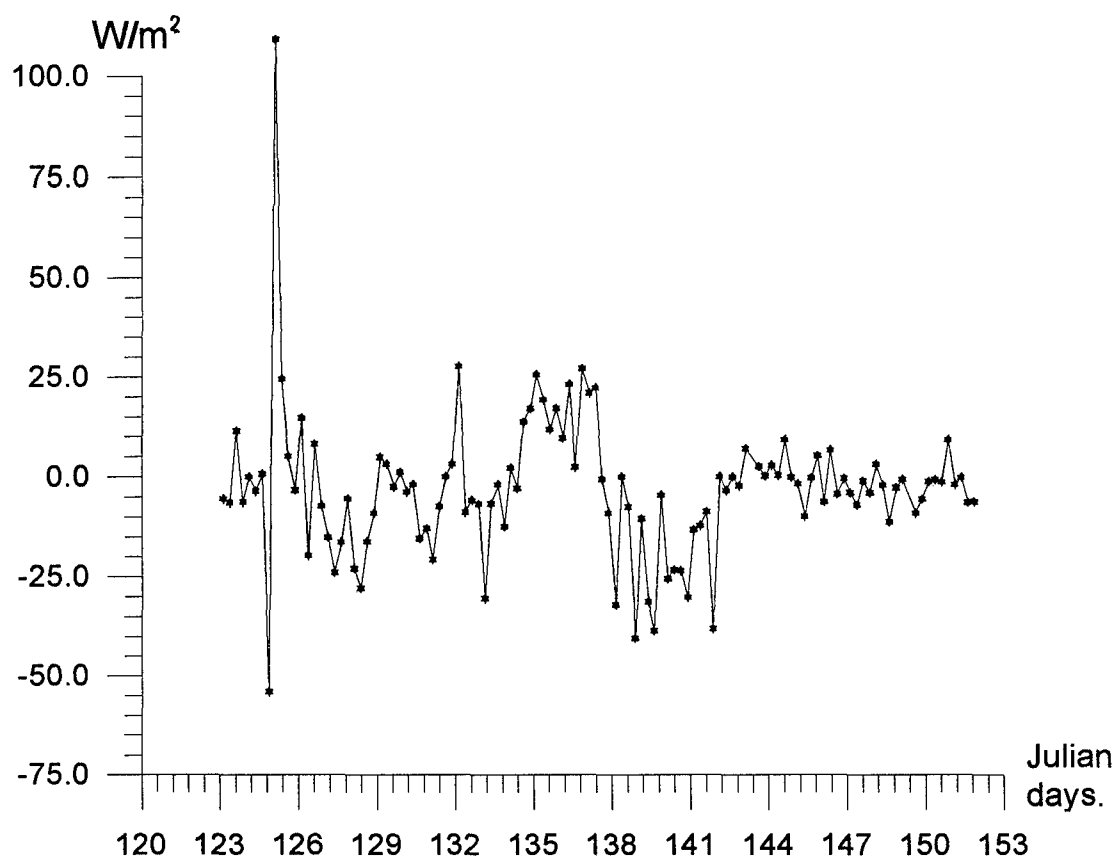
Fig. 1. Variations of the sensible flux. Drifting station NP-4.
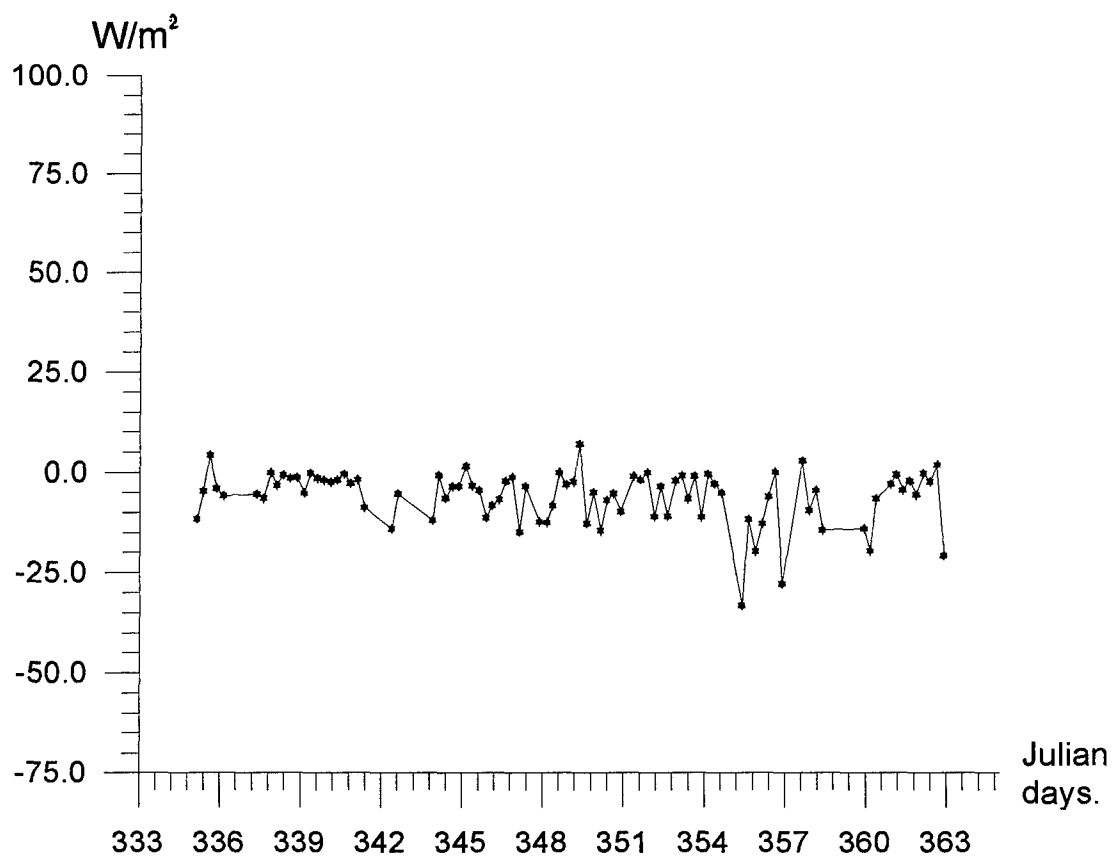May 1956.

Fig. 2. Variations of the sensible flux. Drifting station NP-4.
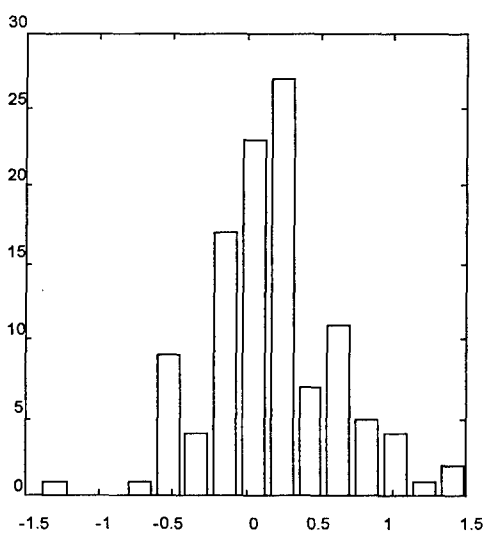December 1956.

**Number
of observations**

Fig. 3. The histigram of distriburion the difference between air temperature on
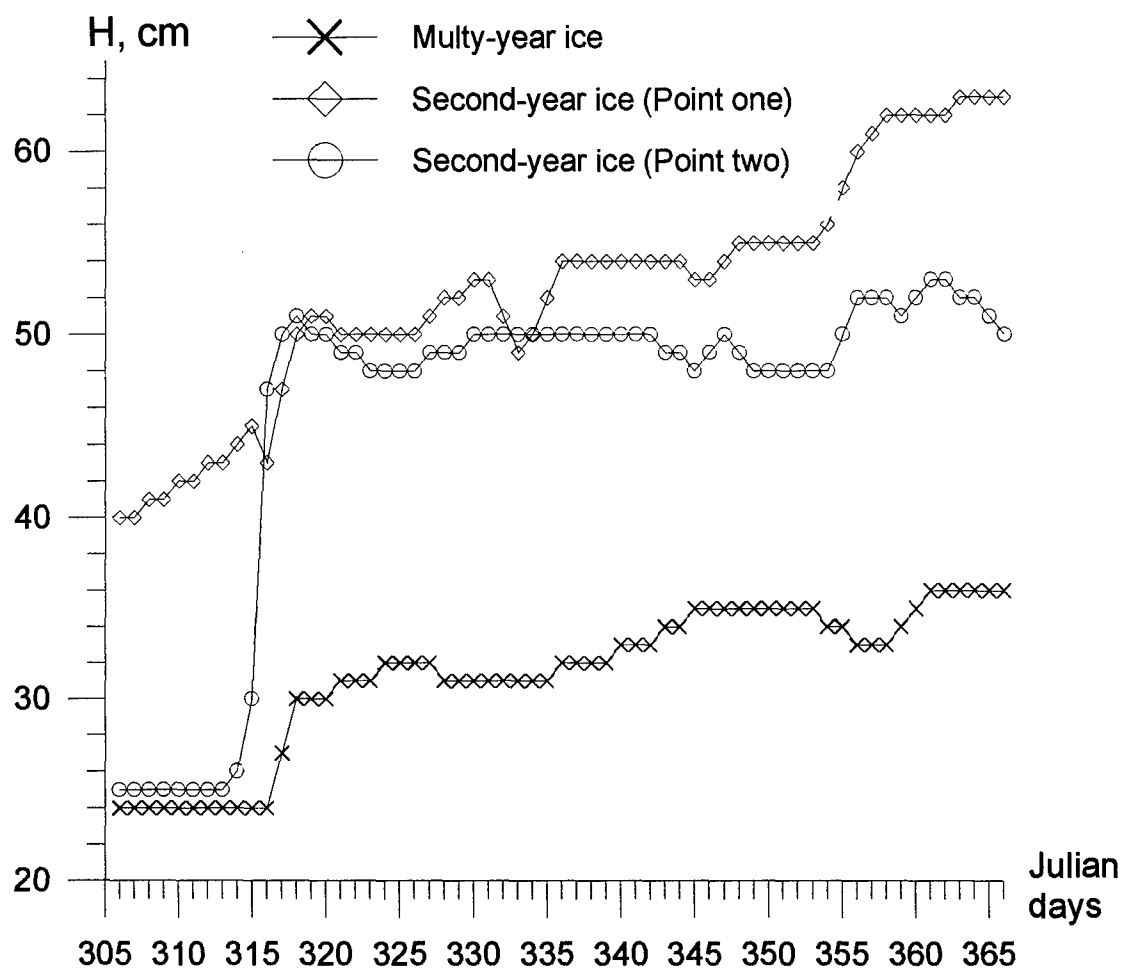heights 2 and 0.2 meters. Drifting station NP-4. May 1956.

Fig. 4. Variations of the snow depth.
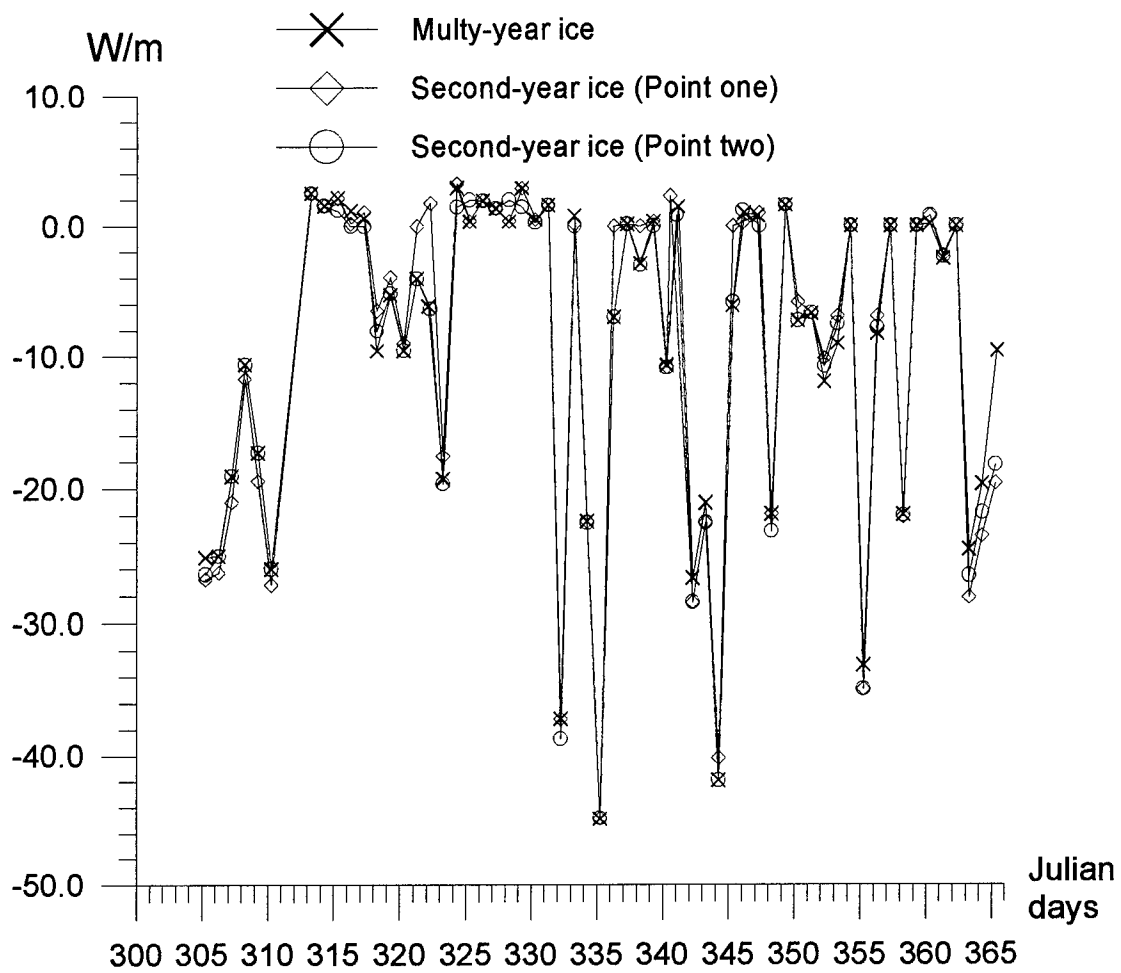Drifting station NP-4, November-december 1956.

Fig. 5. Modelling variations of the sensible flux.
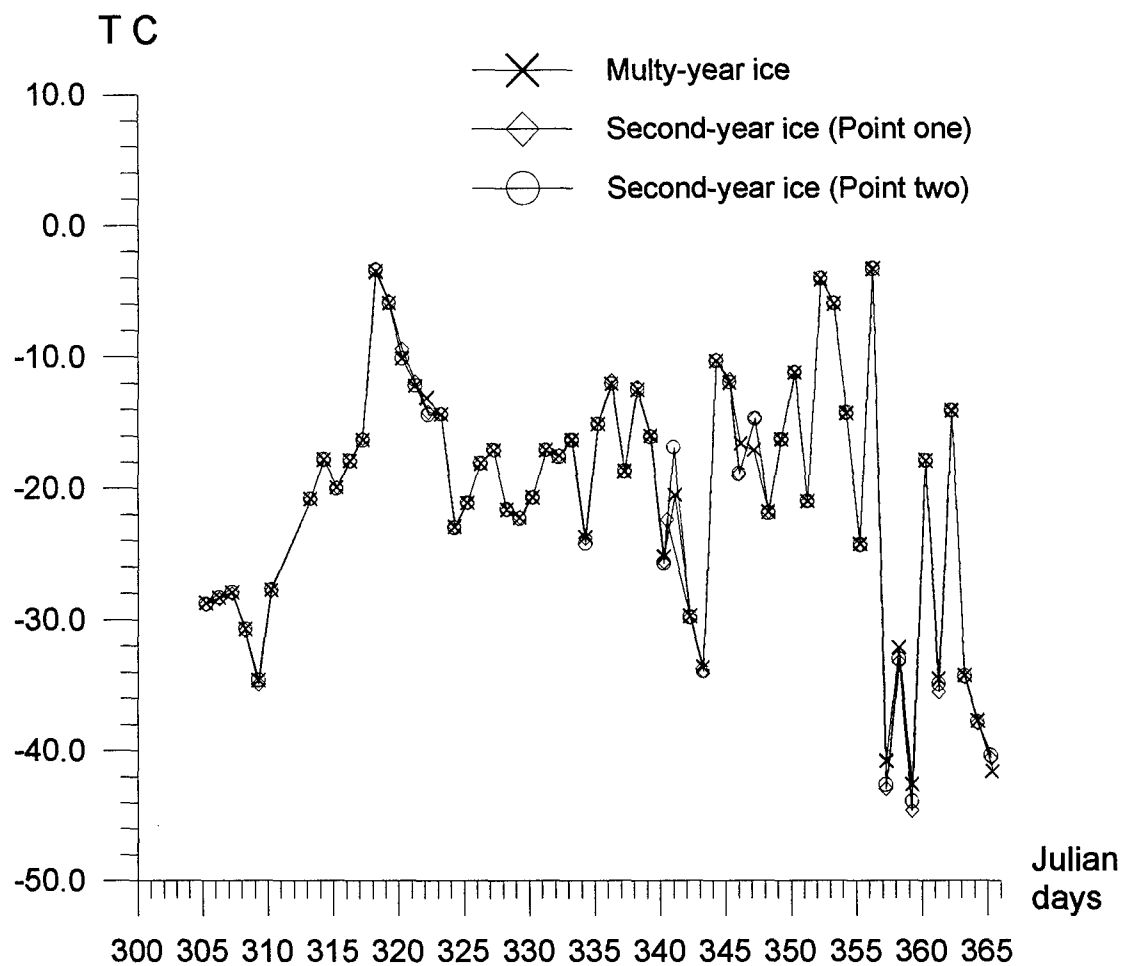Drifting station NP-4, November-december 1956.

Fig. 6. Modelling variations of the surface temperature.
Drifting station NP-4, November-december 1956.